Notes on human error analysis and prediction

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Notes on Human Error Analysis and Prediction

by

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Abstract

The notes comprise an introductory discussion of the role of human error analysis and prediction in industrial risk analysis. Following this introduction, different classes of human errors and role in industrial systems are mentioned. Problems related to the prediction of human behaviour in reliability and safety analysis are formulated and "criteria for analyzability" which must be met by industrial systems so that a systematic analysis can be performed are suggested.

The appendices contain illustrative case stories and a review of human error reports for the task of equipment calibration and testing as found in the US Licensee Event Reports.

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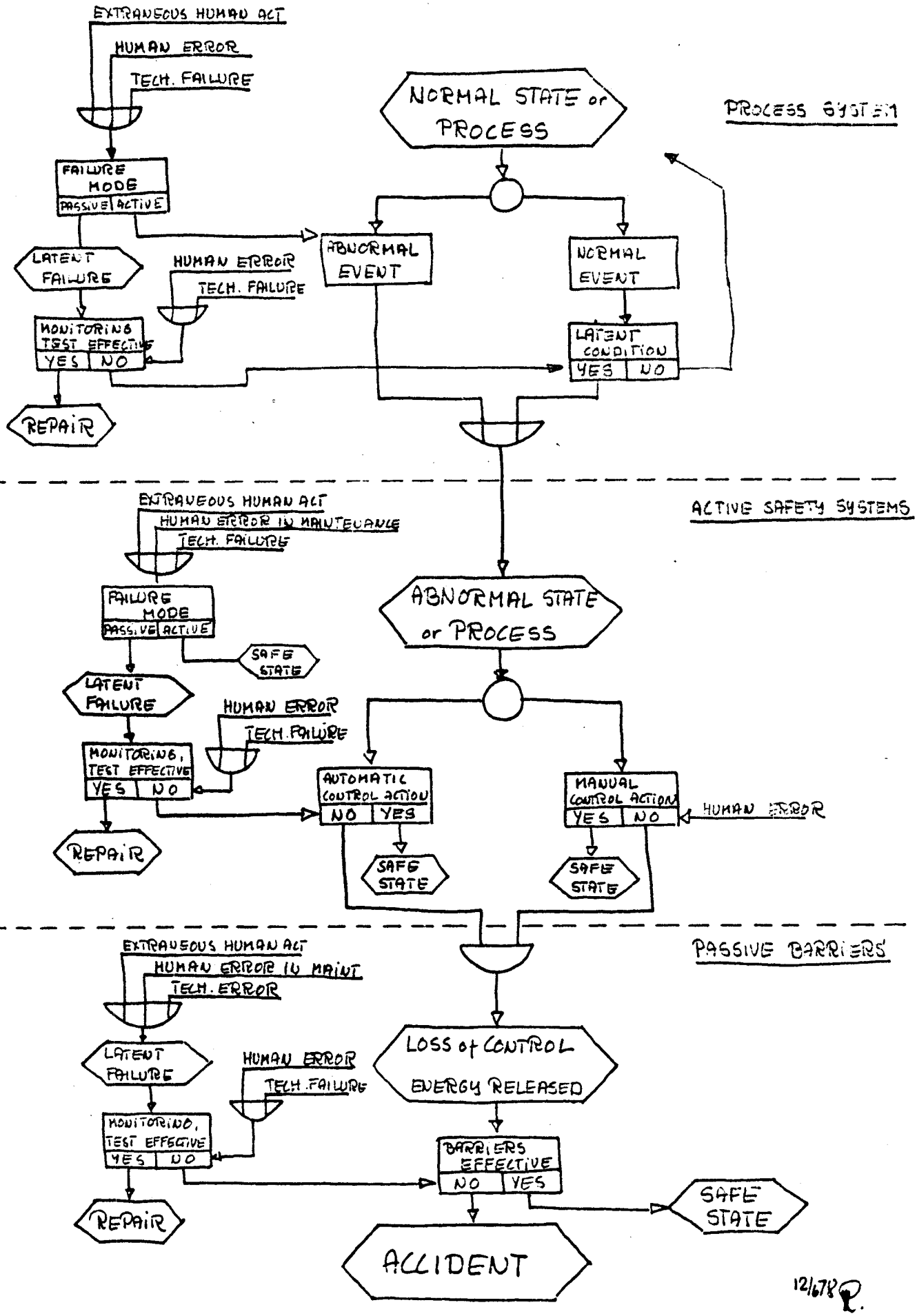
INTRODUCTION

During recent decades the size of industrial process plants has been rapidly increasing and, consequently, designers, users, and society have in general been forced to consider the effects of accidents more carefully, and to take into account the need for protection against large consequence events which, of course, will be of very low probability. Efficient industrial production is tied to large production units, which means large concentration of energy and materials. Therefore, hazard potential cannot be removed completely, and the aim must be efficient hazard control. The complexity of modern process plants together with the rapid technological development, when combined with the low probability of the hazards we are attempting to control, lead to the situation where risk analysis and control cannot be based on empirical design guides and standards. Instead it will require a quantitative analysis of the risk of a system, based on empirical data on the properties of the components and parts of the system. If we sketch the anatomy of an accident in a modern industrial plant, it turns out that the human element often plays a very significant role in the overall performance of the system. Consequently, an increasing effort is being put into the study of human error analysis and quantification. Unfortunately, the need for results has been growing more rapidly than the research needed to supply the basic knowledge on human functions in industrial installations and the related human failure mechanisms. Accordingly, the following review will be as much a review of problems as a survey of possible solutions. However, if the conditions under which present methods are applicable can be stated explicitly, then these conditions can be used as design criteria for systems by serving as "criteria of analysability". Those criteria can then be modified or released as more efficient methods of analysis and better data become available.

ANATOMY of ACCIDENT



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HUMAN ERRORS

Reactor Plant

Cause	Frequency	
. Design Error	38	38
. Operator Error	31	31
Debris in core or system	31	
. Maintenance Error	28	28
Corrosion	26	
. Administrative Error	13	13
Crud (film deposits)	12	
Vibration	10	
Act of God	4	
Grand total	193	110

Percentage Human Error = 57%

(Scott 1971.)

Industrial Boilers

2100 accidents:

39% bad maintenance

19% operator control error

(Ovenu 1969)

Aerospace

Human "Goofs" 50-70% of all failures.

40% {
- 42% Failure to follow procedure
- Incorrect diagnosis
- Misinterpretation of com.
- Insufficient attention

(Cornell 1969.)

Major Events

Human cont ≈ 50-80%

Fault statistics

Human contr. ≈ 10%

RISK ANALYSIS, THEORY, AND PRACTICE

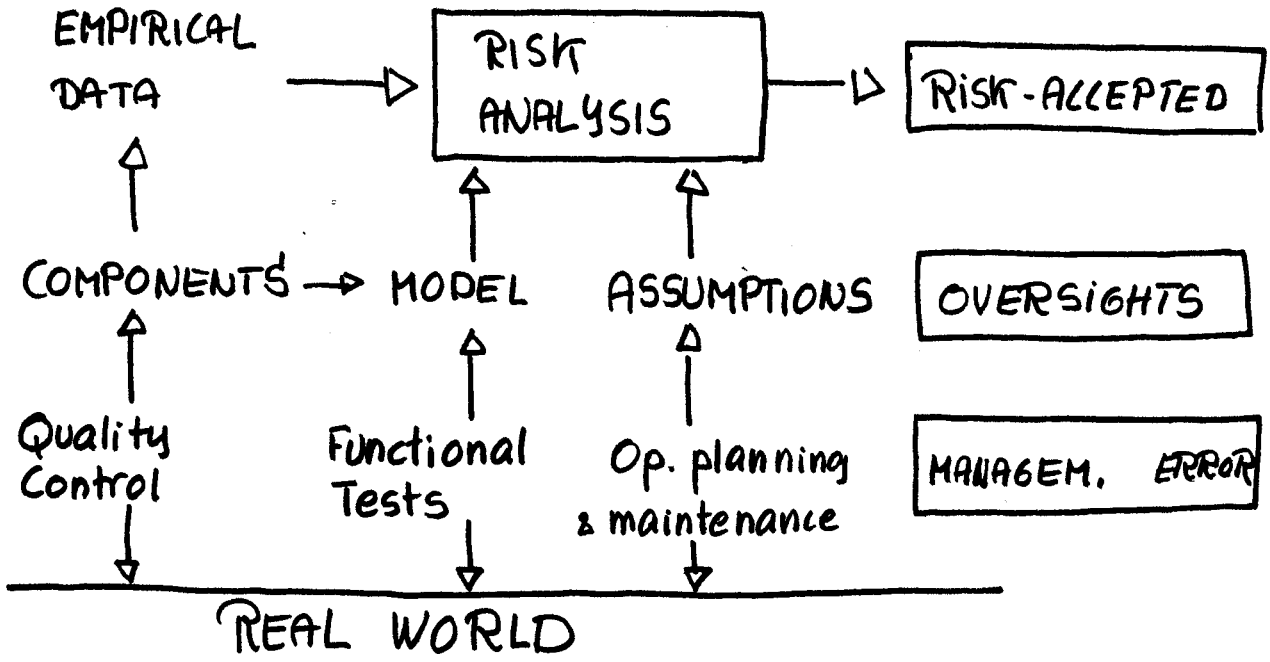
When considering the role of the human element in industrial reliability and safety analysis, it is worthwhile to discuss the relation between risk analysis and the actual, real life risk of losses due to accidental events.

The outcome of a risk analysis of an industrial plant or system is a theoretical construct which relates empirical data describing functional and failure properties of components and parts to a quantitative or qualitative statement of the overall risk to be expected from the operation of the system. This relation is derived from a definition of the boundaries of the system considered, a model describing the structure of the system and its functional properties in the relevant normal and accidental states together with a number of assumptions made to facilitate the mathematical modelling. These assumptions, the model, and the source of the empirical data, are equally as important parts of the risk analysis as the resulting statement of risk level. Therefore, in the overall judgement of the risk potential of the system, it is necessary to consider different categories of risk:

Accepted risks. These are the risks related to the states of accidental maloperation and the causes and effects considered in the analysis. It goes without saying that any risk of unacceptable magnitude uncovered during an analysis will result in a change of the design. The functions of the operating staff in the operation and maintenance of the system will be an important part of this analysis.

Oversights and design errors. The quality of a risk analysis depends upon the completeness of the analysis. In modern complex industrial installations based on very large production units, an important contribution to the overall risk is due to "major loss" situations of very low probability, often resulting from a complex chain of events including coincidence of errors and a priori improbable failure modes. Therefore, sources of risk hidden behind an incomplete analysis become a major problem. Whether such discrepancies between the analytical model and the

CATEGORIES OF RISK



ACCEPTED RISK

OVERSIGHTS & DESIGN ERRORS

MODEL, ASSUMPTIONS, DATA WRONG.

MANAGEMENT ERRORS

REAL WORLD WRONG.

actual plant are considered to be design errors or errors of analysis depends on what is taken for given. The problem of verifying the completeness of an analysis in general and thus insuring that a safety-related design target has been met, can very probably lead to the need for criteria related to "design for risk analysability".

Errors of management. The value of a risk analysis largely depends upon the degree to which the actual, operating plant will satisfy the conditions and assumptions underlying the analysis. Again, this largely depends upon the managerial organization of the plant. This type of risk is related to such activities as planning of quality control, inspection, and testing in order to ensure that the components and parts of the plant do match the populations forming the base for the empirical data, and that the plant is built according to the design specification and will not be subject to modifications and changes without proper risk evaluations. This relates to the technical equipment as well as to selection, training, and organization of operating staff and design of work procedures and instructions.

It lies in the nature of oversights and errors of management that they are tied to human errors, but it also lies in the variety and complexity of organizations and design activities that quantitative risk modelling in these areas is practically impossible. However, a comprehensive qualitative analysis has been made by Johnson (1973).

SYSTEMATIC METHODS VERSUS EXPERT JUDGEMENT

The following discussion of the systematic analysis of the human role in system reliability and safety will be concerned with the analysis behind the first category of risk discussed in the previous section (i.e. accepted risks). It follows from the nature of things that oversights are not included, while errors of management are related to a lack of fulfilment of the basic assumptions of the systematic methods.

However, what is meant by "systematic analysis" is not always evident and invites some discussion. In the present paper, systematic method will be synonymous to engineering analysis when viewed as the alternative to expert judgement, which is taken to be more akin to the performance of a professional art. This distinction also seems to be a distinction which could characterize the difference between reliability engineering and the behavioural sciences.

In general, engineering analysis is based on quantitative data and invariate relations applied to systems and structure which are accessible to inspection or control. Practically speaking, the opposite is the case for the behavioural sciences which depend upon personal, professional skills. It is a "well-known fact that the aim of a skilful performance is achieved by the observance of a set of rules which are not known as such to the person following them" (Polanyi 1958). This also applies to expert judgement which depends upon what Polanyi calls "connoisseurship": "Whereever connoisseurship is found operating within science or technology we may assume that it persists only because it has not been possible to replace it by a measurable grading. For a measurement has the advantage of greater objectivity as shown by the fact that measurements give consistent results in the hand of different people all over the world, while such objectivity is rarely achieved in the case of physiognomic appreciations. The large amount of time spent by students of chemistry, biology and medicine in their practical courses shows how greatly these sciences rely on the transmission of skills and connoisseurship from master to apprentice. It offers an impressive demonstration of the extent to which the art of knowing has remained

unspecifiable in the very heart of science" (Polanyi, op.cit.). This is an important problem when the aim is to include human error analysis and quantification in an engineering analysis of system reliability. Clearly, great care should be taken when including human behaviour in engineering models. In addition, a drastic limitation in the cases which can be handled must be expected, if the analysis is to be based on formalized, systematic methods rather than on expert judgement.

Of course the importance of this aspect depends upon the application of the reliability and safety analysis. If the analysis is used for a relative ranking of different alternative solutions during system design, a number of conditions can be considered equal, and the criteria for analysability will lead to less tight constraints compared with the situation where the analysis aims at a verification or documentation of the design target in terms of quantitative risk level.

A special problem is caused by current developments of large computer codes for overall system reliability and safety analysis. This development is ahead of the formulation of acceptable models of human functions and error mechanisms in the systems under consideration.

Consequently, the only solution for the time being is to include simplistic models of human performance. To be compatible, such models are depending on the mathematical or logical structure of the program rather than on psychological properties. This is acceptable as long as such human error models are used only for sensitivity analysis, to determine the range of uncertainty due to human influences. If quantitative risk figures are derived, these should be qualified by the assumptions underlying the human error models used, and by a verification of the correspondence of the assumptions to the system which is analysed.

"HUMAN ERROR" - DEFINITION AND CLASSIFICATION

The term "human error" is loaded and very ambiguous. Basically, a human error is committed if the effect of human behaviour exceeds a limit of acceptability. Of course, the classification of a specific behaviour as an error depends as much upon the limits of acceptability as it depends upon the behaviour itself. In practise, the limits are often defined after the fact, by someone who can base his judgements on a careful, rational evaluation of the function of the system, while the specific behaviour possibly was a quick response in a stressed dynamic situation. Therefore, as it has been argued by Rook (1965) and Swain (1969), it is necessary to distinguish clearly between errors induced by inappropriate limits of acceptability; i.e., by the design of the work situation, and errors caused by inappropriate human behaviour. Furthermore, as discussed by Rigby (1969), errors can be classified as random errors, due to random variability of human performance such as variations in manual precision or force; differences in timing and simple mistakes and slips of memory; as systematic errors which can be caused by personal abnormalities or inappropriate system design; and, finally, sporadic errors, occasional "faux pas" which are infrequent and often unexplainable erroneous actions. From this definition it follows that it is difficult to give general characteristics of sporadic errors.

The influence from random errors largely depends upon the extent to which the limits of acceptability can be arranged to span the range of natural variability of performance of the people selected to the task, and the opportunity given the operator to monitor his performance and correct the errors he commits.

Systematic errors can be related deterministically to specific properties of the work situation and can be eliminated if the causal relations can be identified and changed. It is a very important category of errors within the context of monitoring and supervisory task in automated systems where the operators typically have to respond to changes in system operation by corrective actions.

In the present general discussion, two types of systematic errors which seem to be important should be considered:

First, human responses to changes in a system will be systematically wrong if task demands exceed the limits of capability. Demands and capability may conflict at several aspects of a task such as time required, availability of state information, background information on system functioning, complexity of data processes, etc. The operator must be able to trade off demands and limitations by choice of a proper strategy. An example would be for the operator to remove time constraints by first bringing the system to a safe, stationary state.

Secondly, systematic human errors may be caused by several kinds of procedural traps. During normal work condition human operators are extremely efficient due to a very effective adaptation to convenient, representative signs and signals. On the other hand, these will very probably lead the man into difficulties when the behaviour of the system changes. An operator will only make conscious observations if his attention is alerted by an interrupt from the subconscious processes. This means that he will only deal with the environment consciously when his subconscious, automated, or habitual responses no longer will control the environment adequately. Likewise, he cannot be expected to cope with a new unique change or event in the system in the proper problem oriented way of thinking if the interrupt is caused by information, which immediately associates to a familiar task or action. It is very likely that familiar associations based on representative, but insufficient information will prevent the operator from realizing the need to analyse a complex, unique situation. He may more readily accept the improbable coincidence of several familiar faults in the system rather than the need to investigate one new and complex fault of low probability. In this way, the efficiency of man's internal world model allows him to be selective and therefore to cope effectively with complex systems in familiar situations, and, at the same time, may lead him into traps which are easily seen after the fact. Davis concludes from an analysis of traffic accidents (Davis 1958):

> "It is usual for a person to have expectations, or to hold to what may be called an hypothesis about every situation he meets, even when information is notably incomplete. This hypothesis, which is in some degree the product of his previous experience of similar situations, governs the way in which he perceives the situation and the way in which he organizes the perceptual material available to him. As he receives further information, his hypothesis tends to be modified or amended or abandoned and replaced. Sometimes, however, an hypothesis and the expectations which go with it, appear to be unduly resistant to change."

The importance of the different categories of errors depends upon the task conditions. In repetitive tasks which are pre-planned, errors due to demands exceeding resource limits and errors due to procedural traps etc., will be of minor importance since when experienced they are readily removed by redesign of the task. Therefore, random errors related to human variability would typically be more prevalent. A review of errors reported from instrument calibration and testing (Appendix 2) indicates as typical errors omission of functionally isolated acts, lack of consideration of secondary conditions, mistakes of alternative possibilities etc.

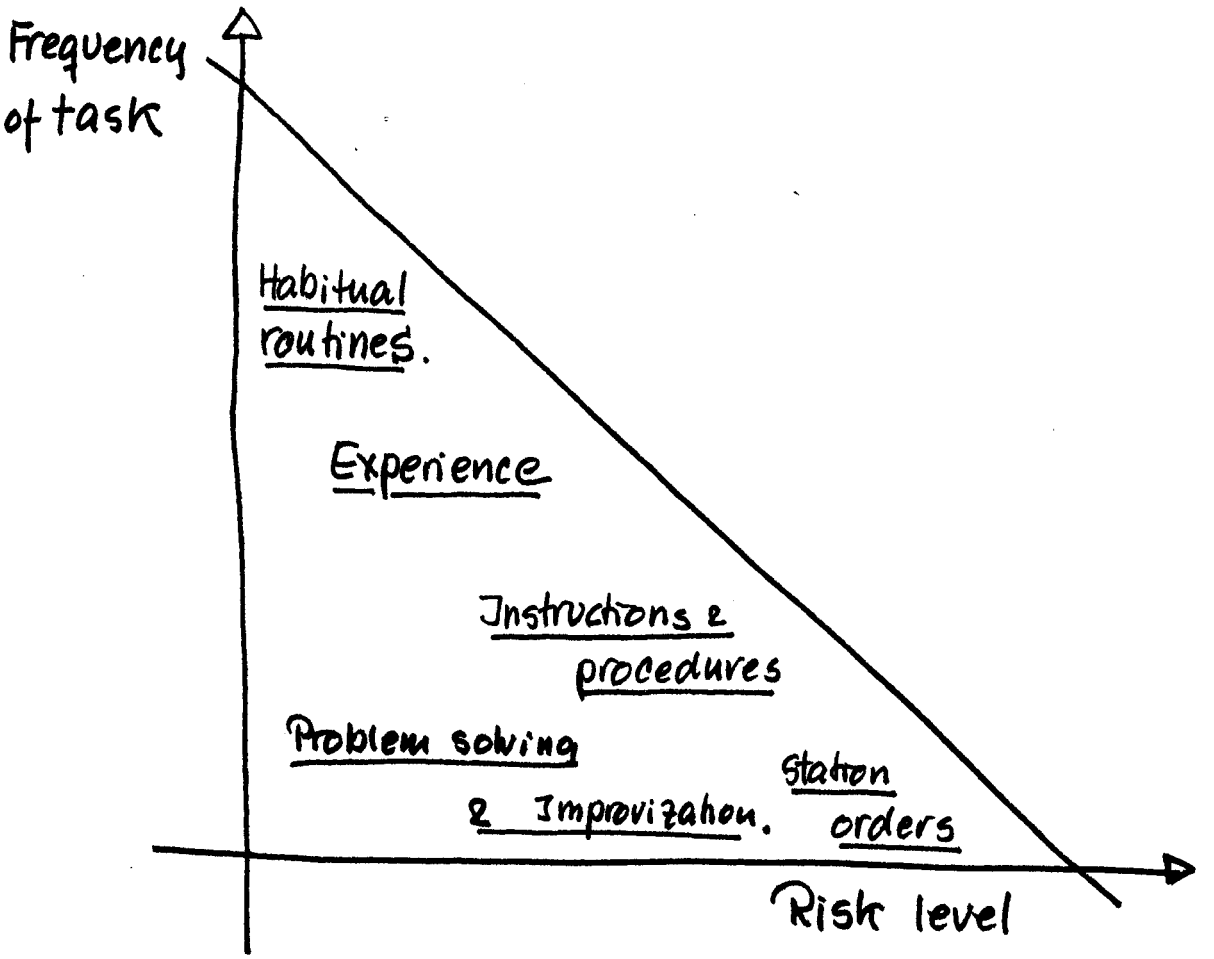
On the other hand, systematic errors are significant contributors when operators have to respond to abnormal plant condition during monitoring and supervisory tasks. Reviews indicate that failure of human operators to identify abnormal states of a plant or system plays an important role in accidents and incidents in complex systems (Rasmussen 1969, Cornell 1968). However, even if the state of the system is correctly identified, the operator may still be caught in a procedural trap. A familiar, stereotyped sequence of actions may be initiated from a single conscious decision or association from the system state. If the corresponding procedure takes some time; e.g., it is necessary to move to another place to perform it, the mind may return to other matters, and the subconscious actions will become vulnerable to interference, particularly if part of the sequence is identical to other heavily automated sequences.

Systematic human errors in unfamiliar tasks are typically caused by interference from other more stereotyped situations and, therefore, the potential for systematic errors depends very much upon the level of the operator's skill. The fact that operators can control a system successfully during a commisioning and test period is no proof that operators will continue to do so during the plant lifetime.

A basic problem when dealing with systematic erroneous responses to unfamiliar situation is the very low probability of such complex situations.

In a properly designed system there should be a reverse relation between the probability of occurrence of an abnormal situation and its potential effect in terms of losses and damage. In modern large centralized systems, the consequences of faults can be very serious and consequently the effect of human errors in situations of extremely low probability must be considered. In such cases, the potential for systematic errors cannot be identified from experience, but only by a systematic functional analysis of realistic scenarios modelling the relevant situations.

Familiarity / severity Relation



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RELIABILITY AND SAFETY ANALYSIS

In discussing the methodological problems of including the human element of a system in a systematic risk analysis, it appears to be practical to consider the problems related to reliability analysis and safety analysis separately.

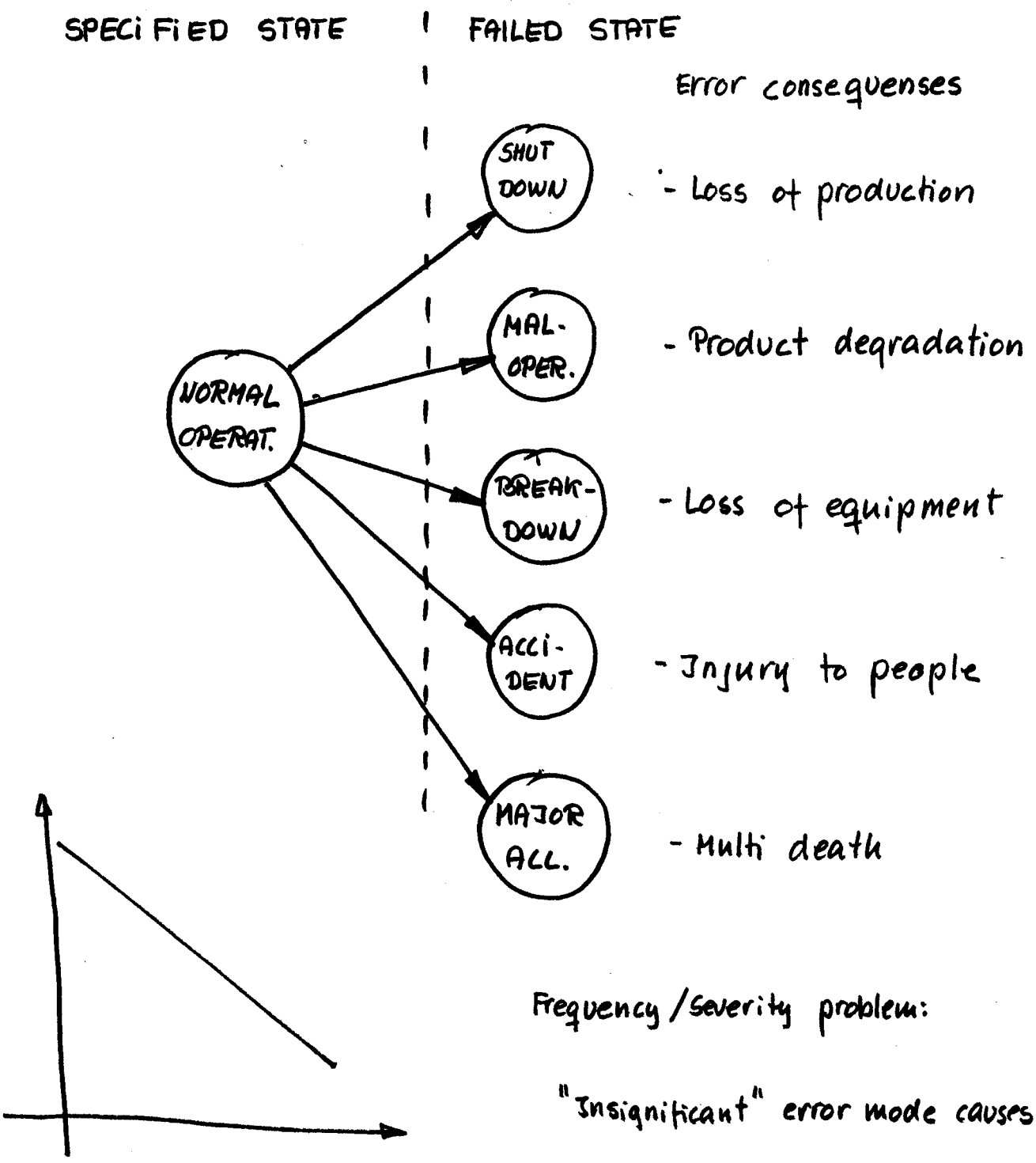
The terms, safety and reliability, are not too well defined. In the following discussion, they are used to characterize two different aspects of the sensitivity to accidental maloperation of a process plant.

Reliability is a measure of the ability of a system to maintain the specified function. Classical reliability analysis leads to figures describing the probability that a system will perform the specified function during a given period or at a given time (M.T.B.F., Availability etc.). Reliability analysis is related to the effects caused by absence of specified function. In case of a process plant reliability, figures are used to judge the expected average loss of production; in case of a safety system to judge the expected average loss of protection.

System safety is a measure of the risk or the expected average losses, caused directly by the presence of a state of accidental maloperation, in terms of human injuries, loss of equipment etc. To judge the safety of a system, it is, therefore, necessary to study the probability of specific courses of events initiated by the primary fault, and to relate the probability to the effects of the maloperation, i.e., judgement of system safety is based upon an extensive accident analysis.

In the following discussion a very clearcut distinction between the methods used for reliability and safety analyses is drawn, and very simplistic descriptions of the methods are used. This is tolerable since the purpose of the discussion is to reach some general conclusions regarding the conditions which should be met by a system in order to make a systematic risk analysis possible.

RELIABILITY / SAFETY ANALYSIS.



Frequency / Severity problem:

"Insignificant" error mode causes

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HUMAN FACTORS PROBLEMS IN RELIABILITY ANALYSIS

The definition of the reliability of a system or system component is generally stated in terms of the probability of a specified function versus time, such as: "Reliability is defined as that characteristic of an item expressed by the probability that it will perform its required function in the desired manner under all relevant conditions and on the occasion or during the time intervals when it is required so to perform" (Green and Bourne 1972).

Reliability analysis is concerned with the departure from the specified function of the plant and its parts and components. "Specified function" is rather stable during plant operation and is unambiguously related to the functional design intention. Therefore, the basis of reliability analysis is generally well established. The basic method of reliability analysis is to decompose a complex system into parts or components, to a level at which component properties are recognized from widespread use, so that empirical fault data can be collected. In principle, this break-down must be carried through to a level where component function is invariate with application. This is possible for many standard components, which are designed for a specific function and used according to specifications in system design, e.g., resistors, pumps. In some cases, however, alternative "specified functions" are possible at the level of break-down at which data collection can be arranged. For example, in practice relays and valves can serve to close or break a circuit. Fault data must then be classified according to the function performed, as the related probabilities of failure may be very different for different functions.

Overall reliability characteristics of the system are derived by means of models representing the relations between component and system failures. The degree of sophistication of the probabilistic system models used to derive reliability figures characterizing the total system depend upon the quality of the component fault data available. If only bulk data on component failure rates are available, as is typically the case for process plant components, simple probabilistic models are used

which represent system structure only as far as to specify whether components functionally are connected in series or parallel during specified system function (reliability block diagrams). If more detailed descriptions of failure mechanisms are available, and if good data are available for failure and repair rates, then much more complete failure modelling becomes worthwhile.

In the methods of human reliability prediction in practical use (Meister 1971, Swain 1973), this technique has been transferred to human performance. The complex and often very system-specific human functions are broken down into typical, recurrent, and elementary functions for which reliability data can be collected. Such elementary functions are in practice only distinguishable by their external effects, and are therefore generally characterized as "subtasks".

This technique must, however, be used with caution, since the human element within a technical system has properties which cause difficulties with respect to the basic aspects of reliability analysis:

Man is an <u>adaptive and learning system element</u>, and may very probably respecify a function or a task. Consider for example a monitoring task from a power plant. The specified task: "If the frequency meter indicates below 58 C/S, disconnect load to save the generator". If an operator has only met readings below 58 C/S due to poor meter performance, he may very reasonably respecify his task: "If ....., then calibrate meter" - and lose a generator (as happened at one stage in the US power black out in 1965). Unless such respecifications are known, reliability prediction will be systematically wrong.

Furthermore, a human operator is a <u>multipurpose element</u>. He may be occupied by another task, and omission of specified function may be due to other events in the system rather than human failure mechanisms.

Man is in many respects a <u>holistic data processor</u> responding to total situations rather than to individual events or system

THERP - Techniques for Human Error Rate Prediction

The steps in THERP are similar to the steps in conventional reliability analysis if human activities are substituted for equipment outputs:

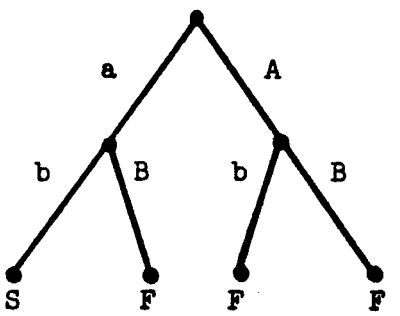
1. Define system failure(s). These are the events for which the influence of human errors is to be estimated.

2. List and analyze the related human operations. This step is the task analysis described in the previous section.

3. Estimate (predict) related error rates (or substitute estimates of error-likeliness).

4. Determine estimated effects of human errors on the system failure events of interest. This effort usually involves integration of the human reliability analysis with a system reliability analysis.

5. Recommend changes to system and calculate new system failure rates. This statement shows the tie-in of the model with MMSA and its use as a tool in human engineering design efforts.



a = probability of successful performance of subtask A
A = probability of unsuccessful performance of subtask A
b = probability of successful performance of subtask B
B = probability of unsuccessful performance of subtask B
S = probability of task success = ab
F = probability of task failure = 1 - ab = aB + Ab + AB

Example 1 - Simple Production Task by One Worker: Assume that a production worker is putting finishing touches on an electronic assembly. Consider that his task on a production line is made up of two subtasks, A and B:

Subtask A. Connect two cables which can be reversed.

Subtask B. Plug in two tubes which can be reversed.

Other errors are possible, but for the purpose of simplicity only the two reversal errors listed above are considered.

Fig. 1. Simplified illustration of the structure of THERP from Sandia Lab. Reproduced from Swain (1976).

states. Complex functions may be performed by skilled operators as one integrated and automated response. In this case fault data can only be obtained by a realistic simulation of the total function (Regulinski 1973). Break-down of complex functions is only acceptable if the performance is paced by the system, i.e., cues from the system serve to initiate elementary skilled sub-routines individually and to control their sequence. This is the case in many manual tasks, e.g., mechanical assembly tasks, but can probably also be arranged by more complex mental tasks by properly designed interface systems.

The failure properties of a specific function depend upon the operating conditions, and for technical components weighting functions are generally used to modify fault data according to load and environmental effects. The great variability of human performance makes a similar weighting of fault data by "performance shaping factors" mandatory (Swain 1973), but the application is difficult as "operating conditions", such as motivation, stress, fatigue, etc., are badly defined and difficult to quantify; "expert judgements" are generally the only method available.

New problems arise if several internal mechanisms with very different failure probabilities can serve the same external component function. The more flexible a component is, the more difficult will these problems be, especially if the internal organization has autonomous features such as optimization, adaptation, learning. These are the prominent features of the human elements in a system. The internal function used to perform a specific external task by a man depends strongly upon his training and skill, his prior experiences of system behaviour, his subjective performance criteria etc. Failure data collected from a system in which an operator meets a specific task frequently, and performs it by a sensory-motor response based on a one-step direct association, will have no relation to the failure probability in a system where the demand for the task is infrequent, e.g., as part of an emergency action. The response must then be performed by a sequence of cognitive functions. The resulting problem can only be solved by classifying fault data according to the internal functions used to perform

a task. In this situation, weighting of fault data collected from standard, frequently initiated tasks, by means of "performance shaping factors" is not acceptable. At present, this means that human reliability prediction is only feasible, if "specified function" of human operators is synonymous with a familiar task performed by a skill maintained through frequent use or exercise.

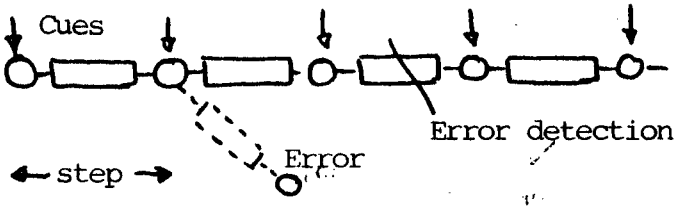
A human trait having great influence upon the reliability of human performance is the ability of selfmonitoring and error correction. The mechanism of error detection depends upon the task situation and the intention of the operator. If the intention is to perform a given sequence of actions, as will be the case in most familiar and stereotyped tasks, error detection will typically be due to difficulties in the sequence caused by errors in the preceding steps. It is obvious that this kind of error detection has drastic effects on reliability. The probability of selecting the wrong key in your key-ring is high; however, the probability that you should not succeed in entering your house of this reason is nil.

In more open and flexible situations, the human intentions will typically be related to attainment of a specific goal, and the reliability in reaching the goal will be related to the persistence in the intention and the care with which a discrepancy is observed or detected, rather than error probability during the striving towards the goal. If you intend to spend a comfortable night reading a good book, the probability of success is not related to the error rate in operating the lamp switch nor to the reliability of the power system, but rather to the probability of having a supply of candles and matches or the proximity of a good restaurant.

Clearly, the error correction features of a task depend upon the structure of the sequence, and not on the individual steps. The potential for error correction influences the reliability of the task drastically and determines which parts of the task should be considered in detail as well as the data needed in an analysis.

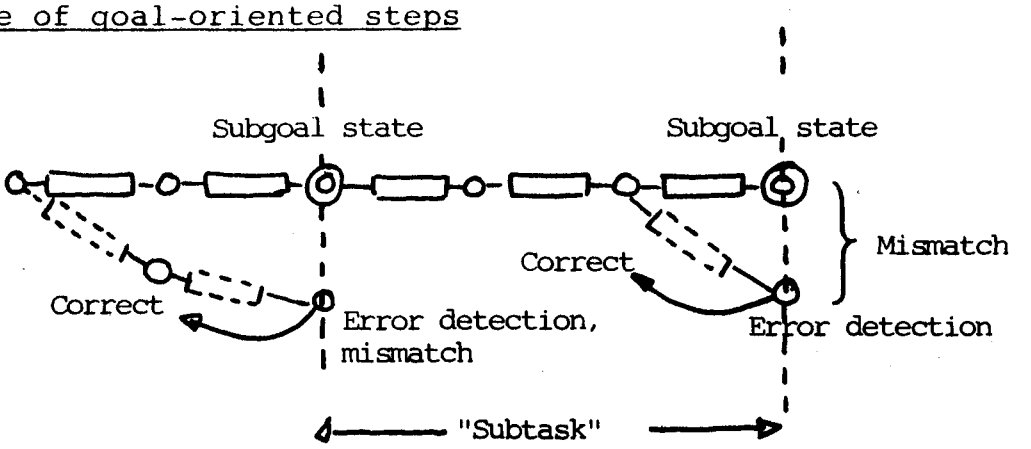
TYPICAL TASK STRUCTURES

Stereotyped Sequence



Simple sequence of steps cued by environment e.g. production and assembling tasks. Error detection typically when subsequent action turns out more difficult. Overall error rate based on error rates of steps must be corrected.

Sequence of goal-oriented steps



Goal-oriented performance facilitates error detection at subgoal nodes - if errors can be corrected by iteration, feed-back effects determine error rates. Overall error rate depends on reliability of error detection. Break-down to elements for data collection only to "subtask" level.

Fig. 2. Simplified illustration of typical task structures

Monitoring and error correction act as a feed back loop around the task performance, and the overall quality of the performance will - as in any feed back system - depend on the quality of the error detection and correction functions, rather than upon the quality of the basic performance itself. In addition to the use of this feed-back feature to improve the reliability of a task design, a proper design of the error detection and correction function can be used as the means for making a reliability analysis of the total task practical, since the lower limit of the overall reliability will be determined by the reliability of the monitoring function alone. This may be the only way to assess the reliability of poorly structured complex human performance - e.g. in response to unfamiliar situations. It should also be noted that the influence of error correction features of a task will lead to a strong dependence of the error rates collected for human actions upon the context from which they are collected.

To sum up, systematic analysis and quantification of system reliability is not feasible unless the design of the system and the work situation of its operators satisfy some general conditions. Necessary conditions for the use of probabilistic methods to predict the probability that a specified task is performed satisfactorily by human operators are:

- there is no significant contribution from systematic errors due to redefinition of task, interference from other tasks or activities, etc.;

and

- the task can be broken down to a sequence of independent subtasks at a level where failure data can be obtained from similar work situations;

and

- these independent subtasks are cued individually by the system or by other external means, so that modification of procedure does not take place;

or:

- if these conditions are not satisfied, e.g., because the task is performed as one integrated whole, or it is performed by complex and variable human functions such as higher level cognitive functions, then the effect of the task must be

GENERAL OPERATOR ERROR RATE ESTIMATE

Estimated Rates	Activity
10^{-4}	Selection of a key-operated switch rather than a non-key switch (this value does not include the error of decision where the operator misinterprets situation and believes key switch is correct choice).
10^{-3}	Selection of a switch (or pair of switches) dissimilar in shape or location to the desired switch (or pair of switches), assuming no decision error. For example, operator actuates large handled switch rather than small switch.
3×10^{-3}	General human error of commission, e.g., misreading label and therefore selecting wrong switch.
10^{-2}	General human error of omission where there is no display in the control room of the status of the item omitted, e.g., failure to return manually operated test valve to proper configuration after maintenance.
3×10^{-3}	Errors of omission, where the items being omitted are embedded in a procedure rather than at the end as above.
3×10^{-2}	Simple arithmetic errors with self-checking but without repeating the calculation by re-doing it on another piece of paper.
1/x	Given that an operator is reaching for an incorrect switch (or pair of switches), he selects a particular similar appearing switch (or pair of switches), where x = the number of incorrect switches (or pair of switches) adjacent to the desired switch (or pair of switches). The 1/x applies up to 5 or 6 items. After that point the error rate would be lower because the operator would take more time to search. With up to 5 or 6 items he doesn't expect to be wrong and therefore is more likely to do less deliberate searching.
10^{-1}	Given that an operator is reaching for a wrong motor operated valve MOV switch (or pair of switches), he fails to note from the indicator lamps that the MOV(s) is (are) already in the desired state and merely changes the status of the MOV(s) without recognizing he had selected the wrong switch(es).
~1.0	Same as above, except that the state(s) of the incorrect switch(es) is (are) not the desired state.
~1.0	If an operator fails to operate correctly one of two closely coupled valves or switches in a procedural step, he also fails to correctly operate the other valve.
10^{-1}	Monitor or inspector fails to recognize initial error by operator. Note: With continuing feedback of the error on the annunciator panel, this high error rate would not apply.
10^{-1}	Personnel on different work shift fail to check condition of hardware unless required by check list or written directive.
5×10^{-1}	Monitor fails to detect undesired position of valves, etc., during general walk-around inspections, assuming no check list is used.
.2 - .3	General error rate given very high stress levels where dangerous activities are occurring rapidly.

Fig. 3. Error estimates, reproduced from WASH 1400.

reversible and subject to an error detection and correction function, which in turn satisfies the above-mentioned conditions for predictability.

In this discussion it has been assumed that empirical data on human error rates in industrial process plants are available. Unfortunately, such data are very scarce. Most of the data discussed in the litterature seem to be derived from the original work done at the American Institute of Research (Payne et al., 1962, Munger et al., 1962) or to be very general estimates. Systematic data collection in industrial plants has not been reported apart from the Licensee Event Reports published by US-NRC (see Appendix 2). Error rates are difficult to derive from these reports because the denominators, the number of error opportunities, are not known. An attempt to estimate the denominators to be used with the Licensee Event Reports has been made by Fullwood et al., 1976.

The data problem becomes even worse, when the reliability of redundant protective systems must be predicted. In this case, the human contribution to overall system unreliability may be due to infrequent errors which are repeated in more channels, i.e. to peculiar systematic errors rather than to random errors from normal human variability.

HUMAN FACTORS PROBLEMS IN SAFETY ANALYSIS

System safety is a measure of the risk - the expected average loss - related to direct effects of the transitions from specified function into a state of accidental maloperation, in terms of human injuries or damage to equipment or environment.

System safety has to be judged from an extensive accident analysis. To identify the course of events following the initiating fault, and to determine the ultimate effect, and its probability, it is necessary to use a detailed functional description of the system including functional properties both within and outside the normal operating régimes of the plant. Different systematic techniques have been developed for this purpose, based on fault tree analysis (Fussel 1973, Powers 1973) and cause-consequence analysis (Nielsen 1971, Taylor 1977).

To evaluate the effects of accidental maloperation, statistical data differentiating the different modes of failure of the components must be available. Furthermore, severe effects are generally results of courses of events of extremely low probability, and may be related to component modes of failure which are a priori improbable and insignificant contributors to component bulk data.

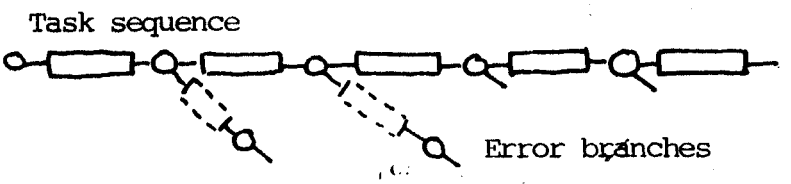
In the analysis of accidents, the human element is the imp of the system. The human reliability, i.e., the probability that operators perform the "specified functions" is of course an important factor in system safety, e.g. when operators are assigned special monitoring and protective functions. In safety analysis, however, a more difficult problem is the analysis of the effect of specific, erroneous human acts. The variability and flexibility of human performance together with human inventiveness make it practically impossible to predict the effects of an operator's actions when he makes errors, and it is impossible to predict his reaction in a sequence of accidental events, as he very probably misinterprets an unfamiliar situation. Some illustrating case stories are found in Appendix 1.

These cases indicate that search strategies used to identify accidental chains of events in the technical system will not be adequate to identify the human potential for creating hazardous situations. In general, search strategies related to fault tree analysis and cause-consequence analysis are sufficient to identify the effects on one part of a system from errors which an operator commits during work on that part due to mistakes etc. However, contrary to reliability analysis, a safety analysis cannot solely be based on search strategies which use the specified task as a guide or structure. Effective search strategies have to take into account the fact that operators are multipurpose components moving freely around in the system. Rare, but risky events in one part of the system can be caused by erroneous acts by operators working on quite different parts of the system; such as disconnection of cables to facilitate vacuum cleaning; interference from manipulation of electric welding gear; short circuits from dropped tools. These types of errors must be found by a search guided by a topographical proximity criterion - analysis of all activity close to the part of the system in question. Furthermore, psychological proximity should be considered. It happens that features of an unfamiliar situation demanding a special procedure instead release an automated routine belonging to other task conditions, especially if parts of the two task sequences psychologically speaking are very similar. Examples are given in the case stories in Appendix 1.

However, a heuristic search based on these criteria may not be sufficient to identify the potential for high consequence, low probability situations which typically are related to complex situations caused by several coincident abnormal conditions and events. A heuristic strategy to identify such situations resembles a design algorithm: First, potential for accidents such as high energy accumulations, toxic material concentrations etc. are identified together with potential targets for accidental release such as people, environment etc. Then possible accidents are designed, i.e., the technical (mal)functions and human actions which are necessary to form the route from source to target are determined. Finally, it is determined how changes in the normal system together with coincident normal and ab-

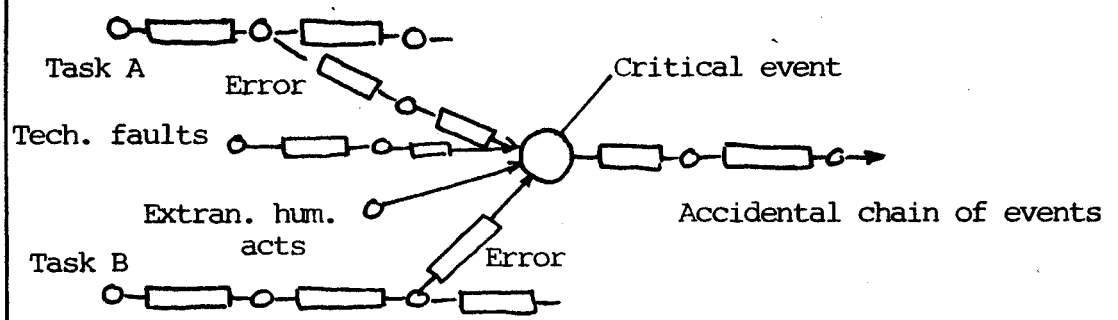
TYPICAL STRUCTURES OF ANALYSIS

Reliability Analysis



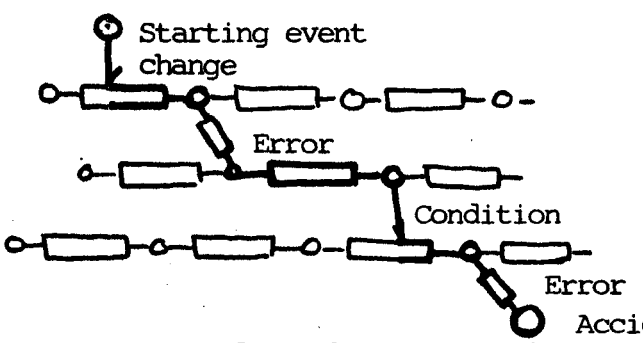
Structure of analysis based on structure of task (compare with THERP).

Safety Analysis



Structure of analysis based on accidental chains of events; analysis and search across tasks; search for sources to critical events (compare with cause-consequence analysis).

Sneak Path Analysis



Several disturbed and normal human activities and technical functions timed for sneak-path

Structure of analysis based on morphological search for routes from accident potential to target. "Design" accident and search for necessary changes (compare with MORT).

Fig. 4. Simplified illustration of typical structures of analysis.

CAUSE-CONSEQUENCE ANALYSIS

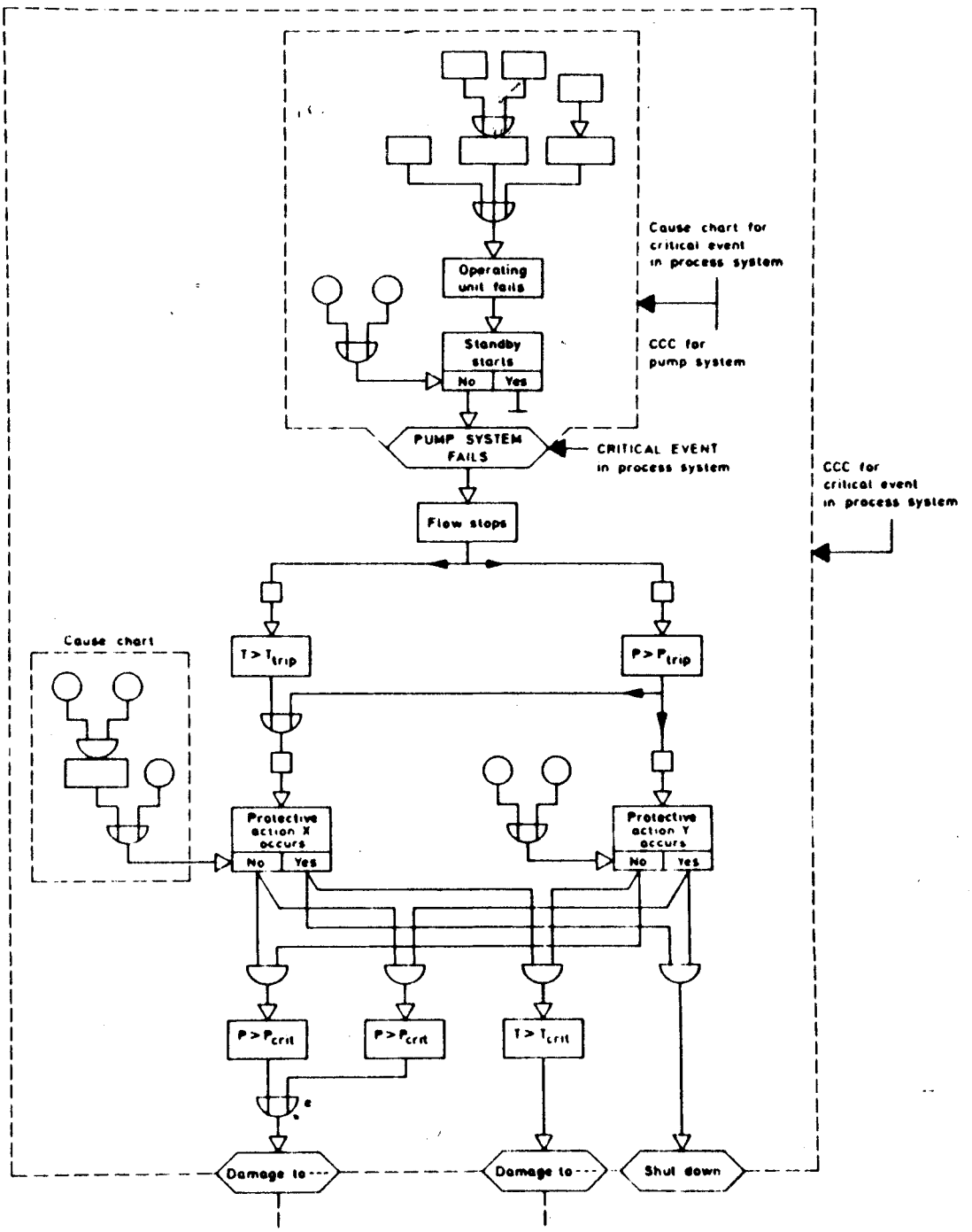


Fig. 5. The structure of a cause-consequence chart for a critical event in a process system. From Nielsen (1974).

CAUSE-CONSEQUENCE ANALYSIS

Assume that this necessary information is available. Assume further that a dynamic model of the plant is available at least at the intuitive level. Some of the main steps in cause-consequence analysis are then:

1. Select a critical event. A critical event is an unintended function of a component directly controlling or affecting main energy or mass balances.
2. Modify the dynamic model taking the critical event into account.
3. Specify the changes/transients of the main process parameters at locations where there are protective devices.
4. Are loading limits for relevant process components exceeded by effects?
5. Identify the environmental changes within relevant areas.
6. Identify "designed protective actions".
7. Construct a consequence chart which shows the potential combinations of "released" and "not released" designed protective actions.
8. For each combination identified in item 7 modify the dynamic model.
9. For each of the identified potential accidents specify the changes/transients of main process parameters.
10. Are loading limits for relevant process components exceeded?
11. Continue the consequence search, if relevant, otherwise go to item 12.
12. Are significant consequences identified? If so, then proceed to item 13, otherwise go to item 1.
13. Identify the potential causes of the critical event.
14. Determine whether accident-preventing or -limiting actions are capable of coping with the critical event.
15. Redesign, if necessary.

Fig. 6. Steps in development of cause-consequence diagrams. Simplified from Nielsen (1974).

MORT - Management Oversight and Risk Tree Analysis

1. An unwanted transfer of energy,

2. Because of lack of barriers and/or controls,

3. Producing injury to persons, property or process,

4. Preceded by sequences of planning and operational errors, which:

   a. Failed to adjust to changes in physical or human factors,

   b. And produced unsafe conditions and/or unsafe acts,

5. Arising out of the risk in an activity,

6. And interrupting or degrading the activity.

Fig. 7. The accident definition which in MORT is used to structure a morphological search for event chains leading to accidents. From Johnson (1973).

normal human activities will meet the designed accident pattern. Such accidents are sometimes due to "sneak paths" which are formed by minor mishaps or malfunctions in simultaneous human activities which only become risky in case of very specific combinations and timing.

In practice therefore, human variability makes a quantitative safety analysis unrealistic, unless the system design satisfies a number of conditions.

Like other problems in system design caused by component performance variability, the problems in accident analysis can be circumvented if feed back functions are introduced, i.e., if feed back links are introduced in accidental courses of events by means of monitoring and correction functions, as it has also been discussed in the previous section.

Major losses or human injuries caused by accidental maloperation are typically related to uncontrolled release of stored energy in the system. Apart from accidents caused by spontaneous fractures of energy barriers and explosions, accidents are typically the effects of disturbances of mass or energy balances. There is, therefore, a time delay between the primary cause and the release due to the integrating effect of a disturbed balance. This time delay makes correcting actions possible.

Furthermore, critical variables related to the energy level of the balance can be found which can indicate potentially risky maloperation irrespectively of the preceding course of events. If a safe state of the system can be defined, and it can be reached through the action of a monitoring and protection function which does not in itself introduce potential risks, an upper bound of the probability of a large class of event sequences leading to the effect which is monitored can be found by a reliability analysis of the protecting function. Such protective functions can be performed by human operators if the task is designed so as to be accessible to human operator reliability analysis, or can be performed by automatic safety systems.

A properly designed protective function enables the derivation of the probability figures needed in accident analysis by means of a reliability analysis of the protective function. Together with data on the frequency of error opportunities, this analysis leads directly to upper bounds on probability of courses of events leading to the effect which is monitored.

It is the extensive use of automatic, protective systems in nuclear power plants that has made it possible to perform a quantitative analysis - including human performance - of the safety level of such installations (Norman Rasmussen et al. 1975).

The difficulty to get the empirical data from real life situations needed to predict the probability of specific erroneous human acts which are possible contributors to rare chains of events leading to accidents, results in the following conditions for quantification of system safety:

The probability of specific consequences of accidental events in a system can only be quantified if:

- it can be demonstrated that the effect of erroneous human acts are not significant contributers to the probability; if necessary by introduction of interlocks or barriers which prevent human interaction;

or

- the effects of erroneous human acts are reversible and detectable by a monitoring or safety function which can be performed by operators or automatically.

If the reliability of such barriers and safety functions can be quantified then an upper bound of the probability of the event in question can be derived from the frequency of error opportunities.

CONCLUSION

In principle, a process plant design, which is not based on extensive experience from similar concepts, is only acceptable if performance design targets can be verified by systematic analysis including a quantitative reliability and safety analysis.

A quantitative safety analysis is only possible if the plant design is performed according to guidelines derived from the limitations of the available methods.

The design must be based upon a qualitative accident analysis. Accident potentials cannot be identified by an evaluation of the effects of all possible courses of accidental events. They must be identified directly by a systematic search. Heuristic search strategies related to energy and poisonous matter concentrations have been developed to serve this purpose (Johnson 1973, Powers 1973).

When accident potentials are identified in this way, the sequences of accidental events, which are capable of triggering an accident, must be identified by a systematic, qualitative cause-consequence or fault tree analysis. If a quantitative probabilistic evaluation of the sequences so identified indicates unacceptable risk - or if a quantitative analysis is not possible due to lack of statistical data, monitoring and protection functions must be introduced in the design.

Such functions must be designed so as to be accessible to a quantitative reliability analysis. During the reliability analysis of complex protective systems, it is generally important to keep track of the temporal relations of events, and simple reliability block diagram analysis must be replaced by more sophisticated methods, such as Markov models, renewal theory etc., compatible with an analysis of causal chains of events.

A protective function can be performed by an automatic system or a human operator.

Reliability analysis of human performance is only feasible if the tasks are performed by sequences of skilled subroutines which are separated and initiated by proper cues from the system. The reliability of more complex and freerunning tasks cannot be predicted directly; an acceptable prediction of results can only be made in this situation if the effects of the actions are reversible and subject to verification by an operator, following a predictable check procedure, or covered by an automatic protective function.

Automation in this way does not remove man from a system, neither does it force him into the role of a trained robot. Automation serves to replace unexpected tasks at unpredictable moments by tasks which can be planned and trained and which can be based upon qualified decisions, such as supervision, test, and maintenance.

A proper design policy will decrease the influence of unpredictable performance shaping factors, such as stress and motivation. When introducing automatic safety systems, the designer takes responsibility of plant safety and thus relieves the operator from stress. The actions of safety systems are related to rather general criteria concerning the initiating plant states and complex, safe protective systems will decrease plant reliability. The operator thus has a supervisory task to protect the plant from unnecessary automatic safety actions. The responsibility of the operators is related to the reliability of plant operation.

The motivation of plant operators can be maintained in automatic systems if they are allowed to use their abilities and take responsibility in the tasks they are allocated. There is no reason not to permit this as long as the system is designed in a way which allows them to verify the effects of their decisions and actions in a predictable way.

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APPENDIX I

CASE STORIES

CASE STORIES

The following case stories illustrate some of the phenomena which make reliability and safety prediction difficult. Unless otherwise indicated, they have been obtained from private communications with process plant operators. In some cases, details have been deleted, to protect both the innocent, and the unlucky.

Case:

During normal operation of a process plant the power supply to the instrumentation and the control console slowly disappears.

Investigation:

The manual main circuit breaker in the fly-wheel motor-generator supply is found to be in the off position. The conclusion of an investigation was that a roving operator, checking cooling towers and pumps, inadvertently had switched from a routine check round to the friday afternoon shut down check round and turned off the supply. The routes of the two check rounds are the same, except that he is supposed to pass by the door of the generator room on the routine check, but to enter and turn off the supply on the shut down check. Something "en route" obviously has conditioned him for shut down check (sunshine and day dreams?). The operator was not aware of his action, but did not reject the condition.

Comments:

Human operators move around in the plant, and it can be difficult to predict where in the causal structure of the plant he interferes. His actions may not be initiated by an event in the system or specified by a program, but by subconscious mechanisms, i.e. it is difficult to predict when he interferes and how.

Case:

During start up of a process plant the plant is automatically shut down during manual adjustment of a cooling system.

Investigation:

During start up the operator monitored the temperature of the primary cooling system and controlled it by switching off and on the secondary cooling pumps to avoid water condensation in the primary system due to the cold cooling water. On this occasion he observed the temperature to reach below the low limit, signalling a demand to switch off the secondary pumps, while he was talking to cooperator over the phone. He then switched off the primary pumps and the plant immediately shut down automatically. He did not recognize the cause immediately, but had to diagnose the situation from the warning signals.

The control keys for the two sets of pumps are positioned far apart on the console. A special routine exists during which the operator switches the primary pumps on and off to allow an operator in the basement to adjust pump valves after pump overhaul while they communicate by phone. Is the cause of the event subconscious switching of procedures due to the phone call?

Comment:

The case illustrates some features of operator behaviour:

- Change in procedures by secondary unpredictable events or conditions.

- The operator introduces couplings in the system by coincident omission of one task and performance of an inappropriate action.

- The risk may be related to the inappropriate and unpredictable act rather than to the omission.

Case:

An experimental plant shuts down automatically during normal operation due to inadvertent manual operation of cooling system shut off valve.

Investigation:

A safety shut off valve in the cooling system which is routinely closed during post shut down check procedures was closed manually. The valve control switch is placed behind the operating console, and so is the switch of a flood lightning system used for special operations monitored through closed circuit television. The switches are neither similar not closely positioned. The operator has to pass the valve switch on his way to the flood light switch.

In this case the operator went behind the console to switch off the flood light, but operated the shut off valves which caused plant shut down through the interlock system.

Comments:

Strongly automated and stereotyped action sequences are frequently initiated by a single conscious decision. If the action takes some time, e.g., you have to move to another place to perform the action, the mind may return to other matters, and the sequence is vulnerable to unpredictable conditions, particularly if the sequence intended in some of the steps overlap other familiar and automated sequences.

Case:

Butadiene explosion at Texas City.
Plant Safety and Loss Prevention. Volume 5, CEP.

Investigation:

"Loss of butadiene from the system through the leaking overhead line motor valve resulted in substantial changes in tray composition ...".
..."The loss of liquid in the base of the column uncovered the calandria tubes, allowing the tube wall temperature to approach the temperature of the heat supply. The increased vinylacetylene concentration and high tube wall temperature set the stage for the explosion which followed".
..."The make flow meter showed a continuous flow; however, the operator assumed that the meter was off calibration since the make motor valve was closed and the tracing on the chart was a straight line near the base of the chart. The column base level indicator showed a low level in the base of the column, but ample kettle vapor was being generated".

Comment:

Wisdom after the event tells that closed valve together with continuous flow signals possible leak, and the risk implied calls for investigation. The skilled operator, however, conforms his observations individually with his expectations or process feel. If abnormal observation refers to a familiar situation, he sees no problem and does not investigate the matter. You cannot predict his response without knowing his daily experiences. It can be difficult to predict the probability that an operator performs a specified function because he may have respecified his function - sometimes with good reason.

This can happen, even if there is a clear prewarning:

Case:

Melt down of fuel element in nuclear reactor. Nuclear Safety, September 1962.

Investigation:

Certain tests required several hundred process coolant tubes to be blocked by neoprene disks. 7 disks were left in the system after the test, but were located by a test of the gauge system that monitors water pressure on each individual process tube. For some reason the gauge on one tube was overlooked, and it did not appear in a list of abnormal gauge readings prepared during the test. There was an additional opportunity to spot the blocked tube when a later test was performed on the system. This time the pressure for the tube definitely indicated a blocked tube. The shift supervisor failed, however, to recognize this indication of trouble. The gauge was adjusted at that time by an instrument mechanic to give a midscale reading which for that particular tube was false. This adjustment made it virtually certain that the no flow condition would exist until serious damage resulted.

Case:

Docket 50219-167: Two diesel generators set out of service simultaneously.

Event sequence:

8.10 permission to perform surveillance test on containment spray system No. 1 including electrical and mechanical inspection of diesel generator No. 1.

8.20 permission to take diesel No. 2 out of service for oil addition.

Both systems out of service for 45 min. Foreman overlooked test of No. 1 system when permitting diesel No. 2 operation.

Comment:

Coincident unavailability of redundant systems caused by improper timing of routine tasks. Difficult to predict due to dependence on station "software" vulnerable for changes and oversight due to absence of cues from the system supporting attention.

APPENDIX 2

REVIEW OF LICENSEE EVENT REPORTS ON CALIBRATION, SETTING AND TESTING

INTRODUCTION

The following reflections on human errors are based on a review of "Licencee Event Reports" as they are edited and compiled by "Nuclear Power Experience"[x]. The reports reviewed are from the January 1978 state of the collection and include those in the category of operator/technician errors: calibration, setting and testing.

In general, reliable statistical information on human error rates related to different types of human errors is difficult to gather from this kind of event reporting. While the denominator problem of obtaining the actual frequency of error opportunities can be solved in principle, the reports do not actually give information on the total frequency of errors committed, but rather the frequency of errors which are not immediately corrected by the operator himself. This means that the frequencies of different categories of errors found in the reports are heavily biased by the actual demands of the task. Clearly, human errors which lead to latent system faults or to effects which are not reversible by immediate counteraction will typically find their way to the reports.

x) Nuclear Power Experience. Edited by Nuclear Power Experience Inc., P.O. Box 544, Encino, California

THE TASK: CALIBRATION, SETTING AND TESTING

To judge the effect of error recovery and to relate the errors found in the reports to task content in general, a description of the task in rather general terms is useful.

Generally the task of calibration is a well defined, proceduralized task. The system states, goals and procedures implied in the task are familiar to the operator and subject to formal instruction and training. The errors to be expected are typically omission of steps in the procedure and faults/mistakes related to rather detailed acts. Problems related to conflicts of goals and misinterpretation of system states, which are typical of responses to unfamiliar situations, are of minor importance in the present context.

The task of calibration consists of subtasks of different content, and a preliminary review of the case stories indicates that the following phases should be treated separately:

1. Establishment of the test circuit. The component or subsystem to be tested is isolated from the plant and connected to the test equipment.

2. The calibration act. The test equipment and/or the subsystem to be tested is manipulated or adjusted according to a specified procedure, and the response is compared/judged according to the specified standard in order to obtain agreement.

3. Restoration of normal operating condition of the system. The test equipment is removed, and the normal "line-up" of valves and switches in the system is restored.

THE ERRORS: TYPICAL CLASSES

A preliminary review of the reports indicated the following crude classification:

Omission of subtask or act

- Functionally isolated acts.
- Administrative acts e.g. logging, reporting.
- Other (e.g. caused by distraction, preoccupation).

Errors in commission of subtask

- Improvisation with insufficient knowledge.
- Secondary conditions overlooked, not considered.
- Misinterpretation of instruction or message.
- Faults and mistakes.
- Manual variability, "clumsiness".

Extraneous acts (i.e. acts affecting other systems)

- Inadequate spatial orientation.
- Manual variability, "clumsiness".

ANALYSIS; OBSERVATIONS AND DISCUSSION

Excluding errors committed during plant commissioning, the review includes 111 cases of operator/technician errors during calibrating, setting and test. No attempt has been made to extract statistically reliable data. Instead, the data have been used to support deductive derivations of error characteristics from the features of the task. See Tables 1 and 2.

The principal observation is the high contribution from omissions of steps in the procedure. It should be noted that nearly all these steps are functionally unrelated to the calibration itself and include such things as return of switches or valves to operating position after test; check of standby channels before disconnecting a channel for test; or purely administrative steps (Table 1). It should also be noted that most of the omitted steps are found in the last phase of the task. One explanation of the large contribution from such omissions could be that the effect of these omissions is not directly apparent which therefore prevents any immediate recovery. However, this may not be the only cause. The fact that the steps omitted are unrelated to the prime goal of the task - the calibration - may in itself lead to a high probability of omission. In an analogous context, Whorf[x)] in analysing causes of industrial fires observes that "the name of a situation affects behaviour" - which can lead to similar effects. It is also noteworthy that this type of error to some extent is repeated in several redundant channels (see Table 2).

Another significant class of errors are "faults and mistakes" which mainly include two types: One is mistakes such as replacement of sample size with that of another task; use of positive correction factor instead of negative; calibration with increasing pressure instead of decreasing, etc. Another type is the faults concerned with incorrect or inaccurate set points. This class of error is most significant within the calibration act itself, which is the only part of the task subject to quantitative specifications and which may lead to mistakes without immediate detectable functional effects. Broadly speaking, we

x) p.t.o.

here have two related kinds of error: Variability and inaccuracy in a quantitatively specified adjustment and mistaken interchange of two or more possibilities.

During the first phase of the task, the establishment of the test circuit, the different types of errors all contribute. This might be expected a priori, since this phase gives the operator most freedom for action, and there will be large differences in task conditions between different types of circuits or components to be tested or calibrated. Again the largest group is omission of functionally isolated - including administrative - acts.

Extraneous acts are found only in this phase, and two types are noted - effects on other systems can be caused by inappropriate spatial orientation such as misplacement of jumpers, or by simple "clumsiness".

One type of error affecting all three phases is due to change of procedures in a way that secondary features affect the calibration, i.e. influence of properties of the system which are not effective or obvious when the prescribed procedure is used. They may have the character of procedure "improvements": Adding recorders (which load signal sources); too rapid adjustments (not considering time constants); use of another available size of filter paper (which changes calibration) etc. This kind of error has some similarity to "omission of functionally isolated acts".

*) Whorf, Benjamin Lee; The Relation of Habitual Thought and Behaviour to Language. In: Language, Thought and Reality. Selected Writings of Whorf. Ed. John B. Carroll, MIT Press, 1956).

PREDICTION OF HUMAN ERROR RATES IN CALIBRATION

Some considerations on predictability can be made at a rather general level, without reference to the particulars of the task.

In the quest for acceptable safety systems, an important contribution to risk analysis will be an estimation of availability of protection. In the present context, the problem then is prediction of human reliability, i.e. the probability that test and calibration leave the system in the specified state. The observations from the event reports can be related to the conditions for analysability of a task for this purpose. These conditions have previously been formulated as follows:

Necessary conditions for the use of probabilistic methods to predict the probability that a specified task is performed satisfactorily are:

1) a. There is no significant contribution from systematic errors due to redefinition of task, interference from other tasks or activities, etc.

   and

   b. The task can be broken down to a sequence of independent subtasks at a level where failure data can be obtained from similar work situations.

   and

   c. The subtasks are cued individually by the system or by other external means, so that modification of procedure does not take place.

   or

2) If task cannot be broken down to independent subtasks, but is performed as one integrated whole or it is based on higher cognitive functions, then the effect of the task must be reversible and surveyed by a predictable monitoring, testing or inspecting function. Reliability analysis of this test function can lead to estimates of limit values of reliability of the task sequence.

The following comments can be made:

1a: Systematic errors play a minor role in the cases considered. They are only present in a few cases as "improvements" of procedures. In general, they can be controlled by proper design of equipment and procedures.

1b: The task of calibration can be broken down into rather independent subtasks which are frequently performed and for which empirical fault data therefore can be collected.

Error rates of the following categories of error are relevant:

- Omission of acts which are functionally isolated from the overall goal of the task sequence to which they are connected.
- Using the wrong alternative of two possible, when the choice has no functional effect upon the subsequent steps.
- Spread in accuracy when adjusting variables to reference values.
- Operational "improvement" of procedures excluding consideration of secondary conditions of no immediate influence upon the task.

(For the cases reviewed, consideration only of "omission of isolated act" during restoration and "faults and mistakes" during the calibrating act could bring a prediction within a factor of 2 from the target, see Table 1).

1c: In case of calibration and testing, control of the sequence of the subtasks can be obtained through functional constraints provided by proper design of equipment.

There is no indication in the cases reviewed that extraneous acts committed during work on other systems or during other activities play any role in the availability of the systems. In some cases miscalibration or defeat of system function is explained in the event report by such extraneous, inadvertent acts, but the number is insignificant.

In conclusion, the features of the task of test and calibration are such that reliability of the task, seen in isolation, can be made predictable by proper design of equipment and procedures.

Special problems are found in redundant safety systems in attempting to predict the probability of repetition of errors in subsequent calibration tasks. The cases reviewed indicate that repetition of "omission of functionally isolated acts" in subsequent tasks plays an important role, but, as could be expected, there is also an indication that systematic errors caused by misinterpretations and operational "procedure improvements" play a much more significant role in the overall reliability of redundant systems. Therefore, to make probabilistic prediction meaningful, strict control of the task sequence and its content by constraints from equipment design is necessary to limit effectively the possibility of improvisation and "improvement". This also places a need for hard constraints upon the managerial system, which can be the source of changes leading to common mode errors.

In passing it should be mentioned that the causes behind the dominant types of human errors can very probably be removed through a proper design of equipment and work content. For instance, equipment can be designed so as to link necessary, but functionally isolated acts, tightly to other acts which lead to immediate apparent functional effects if they are omitted. From the present review of event reports it appears that even a simple reliability analysis of the task sequence, based on human reliability data presently available, can support a redesign of the calibration task.

"HUMAN ERRORS" IN TEST AND CALIBRATION. TOTAL 111 RECORDS

TABLE NO. 1

		TEST CIRCUIT SET-UP		ADJUSTMENT AND CALIBRATION		RESTORATION OF NORMAL OPERATION	
OMISSION	Functionally isolated act	7	- Not switched to calibration before test - No check of redundant channel			5o	- Valves and switches not returned to operational conditions
	Administrative act (log, message etc.)	5	- "As found" valve not logged - Control room operator not informed - Jumbers not logged				
	Other	1		2	- Off-limit value logged, no action	1	- Restart of pump omitted - interrupt from emergency task
ERROR IN TASK	Improvisation, insufficient knowledge	2	- Simultaneous test and start - Transient underestimated				
	Secondary condition not considered	3	- Loading by recorder - Filter paper, wrong size change calibration	3	- Time constants not considered - Signal wire not used as spacer	1	- Test load decreased too rapidly
	Misinterpretation	2		2	- Orders, procedures misunderstood		
	Faults and mistakes	4	- Interchange of channels, valves 522/523; 2SB-1/2SB-2 - Disabling channels concurrently	13	- Wrong sample size, set-point etc. - Interchange set/reset; plus/minus, decreasing/increasing	3	- Corrections reversed, wrong
	Manual "clumsiness"	1	- Inadvertent short-circuit	2	- Inaccuracy, "delicate adjustment"		
EXTR. ACT	Topographic mis-orientation	3	- Jumber misplaced; sneak-path				
	"Clumsiness"	1	- Relay tripped inadvertently				

TABLE NO. 2

HUMAN ERRORS IN TEST AND CALIBRATION

Number of Channels Affected by Error	Number of Cases
1	95
2	11
3	2
4	2
17	1